Seedling Microclimate

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ERRATA: **Seedling Microclimate - Land Management Report 65.**

Page 2, Table 1:

In the row 'Spot scalp', the 'Soil evaporation' column should read "Large increase".

In the row 'Spot scalp', the 'Transpiration' column should read "Large decrease".

Page 4, Figure 3:

Delete "SLOPE(%)" from the x-axis label.

Page 18, Figure 10:

Legend in graph should read "25% STONE".

Seedling Microclimate

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ABSTRACT

The microclimate has a significant influence on the survival and growth of seedlings. Microclimate is affected by macroclimate, site, vegetation and soil factors. The influence of these factors on the light, precipitation, humidity, wind, air temperature, soil moisture and soil temperature regimes of the seedling is explained. Examples of how site preparation can modify microclimate are presented.

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1 SEEDLING MICROCLIMATE AND REFORESTATION

Microclimates are small-scale climates which develop both upwards and downwards from the ground surface where radiant energy and precipitation are received and dissipated. They are regions of great variability in both time and space as a result of variation in weather conditions, terrain, vegetation cover, and soil properties (Caborn 1973). Macroclimate, that is, atmospheric conditions at a scale of 10-1000 km largely determines the microclimatic conditions. Macroclimate is the amount of solar radiation (sunshine) and precipitation received, and the wind speed, temperature, and humidity of the overlying regional air mass.

The influence of macroclimate on plants at a site is the basis of the zone and subzone classification levels of the Biogeoclimatic Ecosystem Classification System (Pojar *et al.* 1988). Divisions within subzones reflect how site factors modify the influence of macroclimatic conditions to produce the microclimate of the site. Examples include the effects of terrain on solar radiation receipt and soil water drainage, the effects of vegetation shading and snow insulation of the ground, and the effects of soil composition and structure on the storage and transfer of heat and water in the soil.

Microclimate plays an important role in the successful establishment of seedlings. Light, temperature, and moisture influence many of the important physical and physiological processes that affect seedling survival and growth. For example, the effect of these three environmental variables on the relative rates of net photosynthesis of spruce is shown in Figure 1. Low light levels significantly reduce net photosynthesis, as do air temperatures below 5 and above 30°C. If root zone soil dries appreciably, net photosynthesis also declines as the seedling experiences increasing levels of water stress.

Extremes of light, temperature, and moisture can physically damage and sometimes kill seedlings. Usually the adverse effects of climate are only noticed when lethal damage occurs. However, sublethal effects are also important because they can reduce the growth potential of the seedling, increase its vulnerability to additional environmental stresses, and increase its susceptibility to disease and insect infestation.

For reforestation to be successful, it is important that the forester match the silvical requirements of the species to be regenerated to the site environment. Failure to consider the seedling environment can lead to either a complete plantation failure or the creation of an off-site plantation that might grow slowly or be repeatedly damaged by adverse weather.

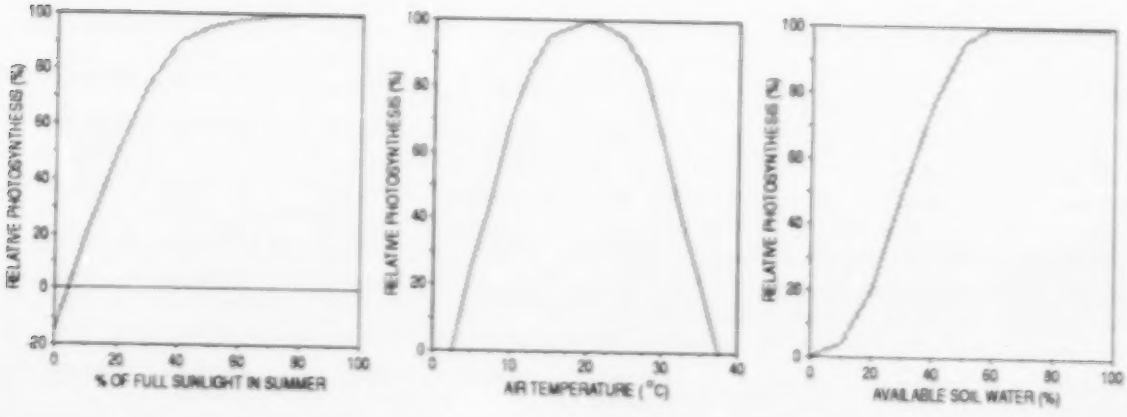

FIGURE 1. The effect of light, air temperature, and available soil water on the relative rate of net photosynthesis of spruce.

Weather conditions, site factors, and forest management activities interact in a complex way to determine seedling microclimate. Recognizing the potential microclimatic limitations of a planting site is an important aspect of the pre-harvest prescription process. The forester must understand how silvicultural treatments affect the receipt and distribution of energy and water at the ground surface, and how soil factors affect the movement and storage of heat and water in the soil. This knowledge will aid the forester in determining the site preparation objectives for a given site, and in evaluating which site preparation treatments can best produce the required seedling microclimate within the limitations of such factors as cost and equipment availability. A summary of the effects of silvicultural treatments on the seedling environment is presented in Table 1.

The following sections present information on the seven environmental variables (light, precipitation, wind, humidity, air temperature, soil moisture, and soil temperature) that determine seedling microclimate. Each section describes how the variable affects seedling survival and growth; how site, vegetation, and soil factors interact with macroclimatic factors; and how site preparation treatments can modify seedling microclimate. References are given where results of specific experiments are presented. The following general references are recommended for those wishing more detailed information on plant microclimate: Bohren (1987) - atmospheric physics; Brady (1974) - soil properties; Campbell (1977) - environmental variables; Childs *et al.* (1989) - soil properties; Gates (1980) - radiation; Geiger (1965) - microclimate; Grace (1983) - plants; Hillel (1971) - soil water; Jones (1983) - plants; Sakai and Larcher (1987) - plants and low temperature; McIntosh and Thom (1972) - weather; Oke (1978) - climatology; Stathers (1989) - frost.

TABLE 1. Effect of site preparation methods on the physical environment of seedlings. Increase or decrease refers to a change relative to no treatment of dense competing vegetation. (Adapted from Spittlehouse and Childs 1990.)

Site treatment	Light	Soil temperature	Soil moisture	Soil evaporation	Trans-piration	Frost hazard	Area of impact
Herbicide	Increase, some shading	Increase	Large increase	Little change	Decrease to zero	Depends on vegetation	Either whole site, or around seedlings
Mulch	Increase	Decrease at depth	Large increase	Large decrease	Large decrease	Increase	Around seedlings
Slash piles	Increase, some shading	Increase	Small increase	Small increase	Little change	Decrease	Variable and not uniform on site
Shadecard	Decrease, shaded	Decrease at surface	Small increase	Little change	Little change	Little change	Very small area around seedlings
Spot scalp	Increase	Increase	Increase	Large	Large	Decrease	Around seedlings
Broadcast burn	Increase	Increase, wider range	Increase	Small increase	Decrease	Decrease	Whole site, variable
Trench	Increase	Increase	Increase	Increase	Decrease	Decrease	Around seedlings
Ripping	Increase	Increase	Increase	Increase	Decrease	Decrease	Whole site
Mounds	Increase	Increase, wider range	Decrease, (increased drainage)	Increase	Decrease	Decrease	Around seedlings
Deep ditches	Increase	Increase, wider range	Decrease, (increased drainage)	Increase	Decrease	Decrease on berm	Around seedlings
Shelter-wood	Decrease, sunflecks	Decrease, narrower range	Small increase	Slight decrease	Increase, from depth	Large decrease	Whole site, not uniform over site

2 LIGHT

Light, or photosynthetically active radiation (PAR), is the visible portion of the solar radiation spectrum. These wavelengths are absorbed by plants and used in photosynthetic reactions. Light accounts for about 45% of the energy from the sun; the remaining 55% is in the non-visible part of the solar spectrum.

2.1 Effect on Seedlings

Most of the sun's energy heats the seedlings' environment and evaporates water. Photosynthesis uses only 2 to 5% of the energy. However, the light absorption mechanisms of the plant require about one-third to one-half of full summer sunlight to achieve maximum photosynthetic rates (Figure 1). Light levels less than about 10% of full sunlight are not adequate to give photosynthetic rates high enough to provide sufficient carbohydrates to replace those used in respiration. Consequently, heavily shaded seedlings accumulate little biomass, grow slowly, and have a spindly growth form (Draper *et al.* 1988; Öerlander *et al.* 1990).

2.2 Factors Affecting Light

2.2.1 Macroclimatic factors

Sunlight varies with the **time of the year**. On clear days at 50°N, mid-summer sunlight is 10 times that in mid-December. **Cloud** absorbs and reflects solar radiation and reduces the amount of photosynthetically active radiation that is transmitted toward the seedling.

2.2.2 Site factors

Slope and aspect have a major influence on the amount of solar radiation received above a vegetation canopy (Figure 2). However, these factors have a much greater effect on site warming than on photosynthesis.

Latitude affects day length and the intensity of solar radiation. At higher latitudes, longer days during the summer tend to compensate for the reduction in solar intensity. This can be beneficial for seedling photosynthesis because much less than full sunlight is required for maximum photosynthesis.

2.2.3 Vegetation factors

The amount of **surrounding vegetation** regulates how much solar radiation reaches the seedling and the soil surface. An individual leaf typically absorbs or reflects more than 90% of the incoming solar radiation. Photosynthetically active radiation below the vegetation consists of the small transmitted fraction and any direct and diffuse light not intercepted by the foliage. The height, density, and leaf orientation of the vegetation canopy surrounding the seedling control light interception. Light levels are usually suboptimal in tall, dense canopies that completely cover the ground. If the vegetation canopy is dense but patchy or discontinuous, light levels in the open areas are usually adequate for seedlings.

Competing vegetation species vary in how they affect the light received by the seedling. This is related to differences in the timing and rate of development of foliage through the growing season, as well as to the height and density of the leaf canopy. Figure 3 shows the percentage reduction of light at the top third of a seedling crown in fireweed, ladyfern, and thimbleberry canopies. Fireweed develops a dense canopy much earlier than the other species, but also begins to senesce earlier. An alder canopy also develops early in the growing season and the foliage lasts into the fall. LePage[1] measured light levels below an alder canopy in the Sub-Boreal Spruce zone that were 25% of those above the canopy. Light levels in seedling microsites within the understory were reduced to less than 10% of above-canopy light.

2.3 Site Preparation and Light

A poor light regime is often a serious problem in many of the wetter subzones in British Columbia. Herbicides and mechanical treatments are used in controlling the vegetation. An example of the effect of

[1] LePage, P. 1989. B.C. Forest Service. Unpublished data.

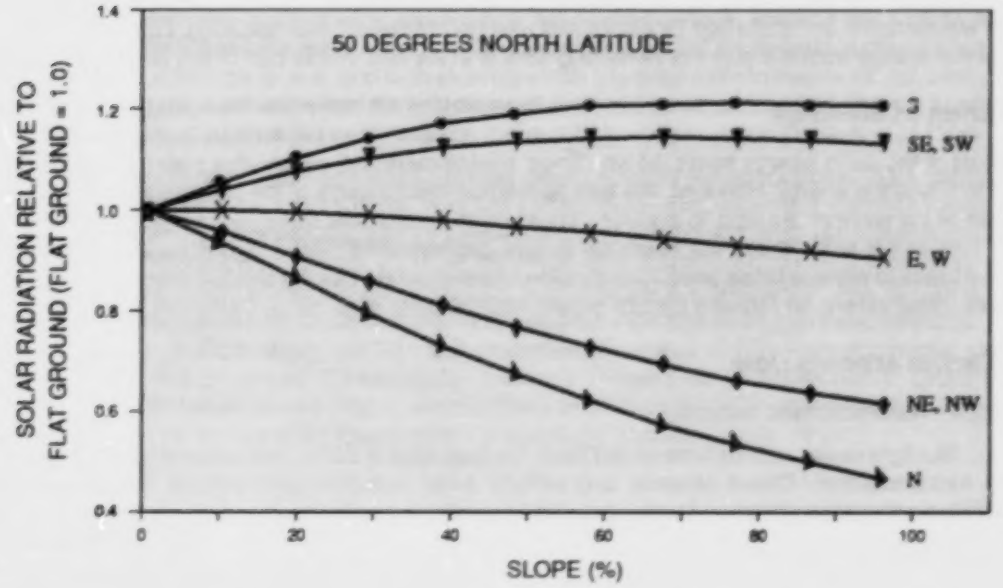

FIGURE 2. The ratio of sloping surface to horizontal surface annual clear-sky solar radiation at 50° north latitude.

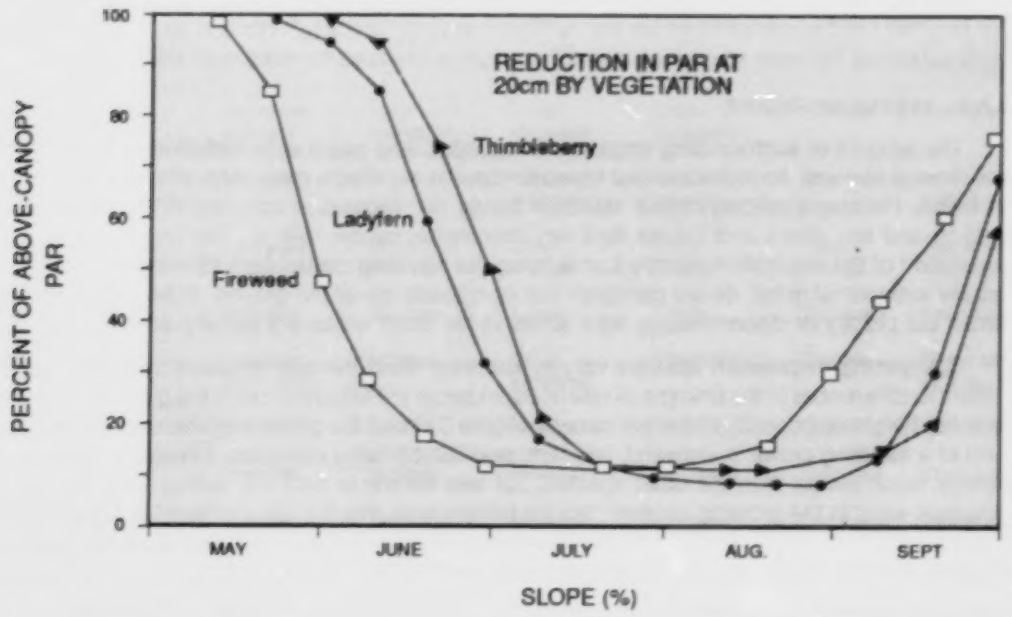

FIGURE 3. The effect of fireweed, ladyfern, and thimbleberry communities on the receipt of photosynthetically active radiation (PAR) at seedling height through the growing season in the Sub-Boreal Spruce zone near Prince George. (Adapted from Draper *et al.* 1988, and C. DeLong 1989, B.C. Forest Service, unpublished data.)

mounding on light levels in a dense ladyfern canopy is shown in Figure 4 (Draper *et al.* 1988). The mounding treatment cleared an area of about 0.6 m in diameter and resulted in light levels that averaged 70% of that above the canopy. Light levels within the untreated ladyfern canopy were below the light saturation point for seedling photosynthesis throughout most of the day, even on sunny days, and averaged only 10-15% of the above-canopy sunlight.

Other benefits of removing dense vegetation canopies include a decrease in vegetation press, and an increase in soil temperature at sites with a thin surface organic horizon (see Section 8 on soil temperature). In hot, arid areas, growth and survival are improved by leaving shade for seedlings, e.g., shelterwoods. In this situation, the reduction in heat stress is of more importance than the loss in photosynthetic potential (Childs and Flint 1987; Hungerford and Babbitt 1987).

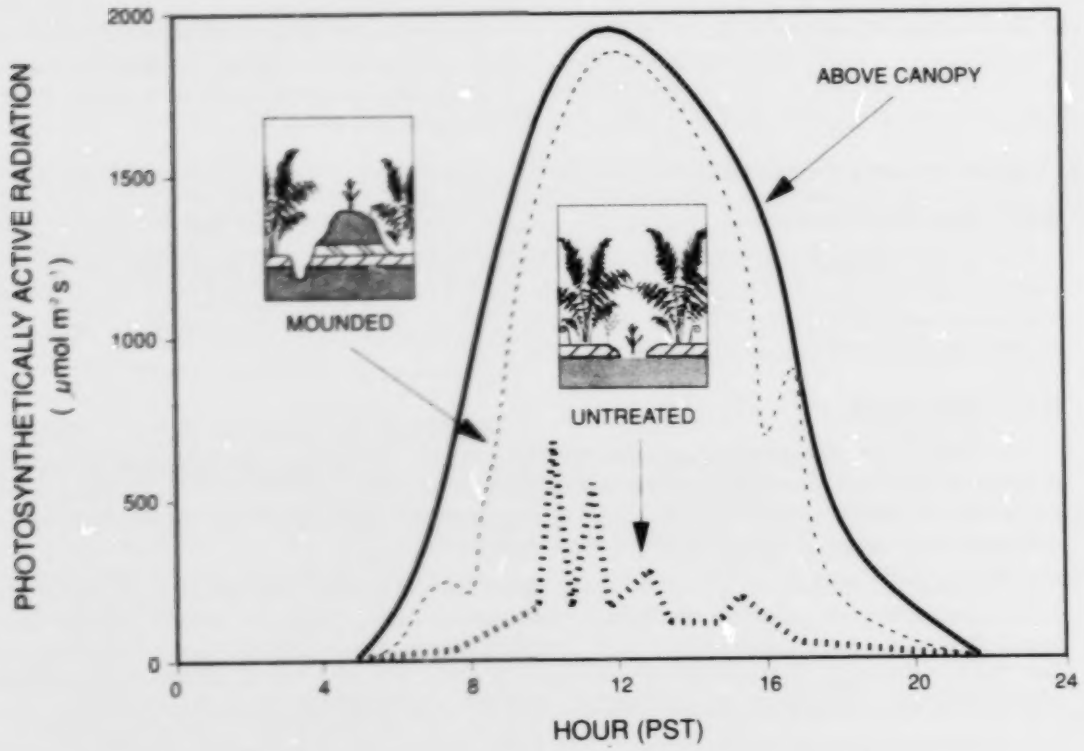

FIGURE 4. Daily course of photosynthetically active radiation (PAR) received by a seedling in a ladyfern canopy and for a mounding treatment, and the PAR above the canopy on a clear day in the Sub-Boreal Spruce zone near Prince George. (Adapted from Draper *et al.* 1988.)

3 PRECIPITATION

3.1 Effect on Seedlings

Precipitation provides the soil moisture used by the seedlings to meet the evaporative demand of the atmosphere. Microsites that have a low soil water storage capacity in the root zone require frequent rainfalls to ensure that seedlings can survive periods of summer drought. Without adequate root zone soil moisture, seedlings can experience high levels of water stress that can reduce growth (Figure 1).

The importance of the rainfall distribution throughout the growing season, and of year-to-year variations in rainfall are discussed in Section 7 on soil moisture. Excessive amounts of snow melt or rain can result in wet, cold, poorly aerated soils (see Sections 7 and 8 on soil moisture and temperature), and erosion of soil in exposed areas.

Snow accumulation on a site can be both beneficial and detrimental to seedlings. Snow cover provides insulation from cold winter air temperatures and alternating winter warming and freezing conditions. **Snow press, down-slope movement of the snow pack,** and **the late melting of deep snow packs or snow drifts** can harm seedlings by deforming stems and increasing their vulnerability to shrub competition and snow molds. Snow can also affect silvicultural operations, for example, by restricting site access or delaying planting. On many of the drier sites, however, snow melt provides the water required to recharge the soil.

3.2 Factors Affecting Precipitation

3.2.1 Macroclimatic factors

The **type of storm**, whether frontal or convective, determines the amount and areal extent of the precipitation. Convective storms usually occur in the summer and can be localized; whereas frontal storms are larger and provide more uniform rainfall over the landscape. The **time of the year** affects amount of precipitation received and the form (rain or snow).

3.2.2 Site factors

Precipitation is affected by **geographic location**, e.g., distance from the coast or other large bodies of water; and by large scale **topographic features**, e.g., windward slopes that face the prevailing storms or leeward rain shadows. Precipitation generally increases with **elevation** in any one area. Snow depth and duration of snow cover also usually increase with elevation.

Depressions, lee slopes, and other areas where drifting of snow occurs can have higher snow accumulations than ridges where wind scour reduces accumulation. **Surface residues**, e.g. stumps and logs also influence snow accumulation. Wind scour can decrease snow accumulation near stumps, logs, and brush. In the spring, these darker surfaces increase the rate of snow melt by absorbing solar radiation and becoming a source of stored heat which melts the surrounding snow.

Snow press depends on the degree of settling of the snow pack. The effect of vegetation press can be enhanced by snow press. The down-slope movement of the snow pack depends on the **depth and density of snow**, the **slope angle** and the **slope roughness**. There is a low risk of down-slope movement on sites with slopes of less than 20°, at lower elevations, or in areas where less snow occurs, and on sites that have rougher surfaces such as rock outcrops, stumps, mounds, and brush cover. Steep, smooth, grassy surfaces with few large surface irregularities, and with deep snow are at a higher risk for snow movement (Megahan and Steele 1987).

3.3 Site Preparation and Snow

Snow damage can be reduced on high risk sites by the establishment of barriers to snow movement through either partial cutting or planting behind stumps and brush (Megahan and Steele 1987). Serious snow damage to seedlings, or the restriction of forestry operations, may not occur every year because of the yearly

variation in the amount of snow accumulated. However, seedlings are vulnerable to snow damage for a number of years after planting. In the first few years, the combined effects of vegetation and snow press are likely to cause the most damage. At high risk sites, down-slope movement of snow can cause problems until stem diameters grow to approximately 10 cm.

Snow accumulation is affected by cutblock size, with small openings (width up to 10 times tree height) enhancing snow accumulation (Golding 1982). The timing of snow melt in clearcuts is different from that in forests, producing differences in the pattern of stream flow (Troendle 1987; Berris and Harr 1987).

In low snowfall areas, surface residues can be used to minimize the loss of snow during the winter from drifting and evaporation.

4 ATMOSPHERIC HUMIDITY

4.1 Effect on Seedlings

The water vapour content of the air (the vapour pressure or vapour density) directly affects the atmospheric evaporative demand on seedlings and, therefore, the seedling transpiration rate. Prolonged high evaporative demand for moisture can cause seedling water stress and a subsequent reduction of growth.

Seedling transpiration rates are influenced by the **vapour pressure deficit**. This is the difference between the vapour pressure in the leaf (which depends on needle temperature) and the vapour pressure of the air adjacent to the leaf. Vapour pressure deficits usually reach a maximum in the mid-afternoon when air and needle temperatures are highest. The **relative humidity** of the air is the ratio of the actual vapour pressure to the saturation vapour pressure. Increasing the vapour pressure deficit (decreasing the relative humidity) of the air increases the evaporative demand, and increases the potential for plant water stress. Winter desiccation often occurs when needles are exposed to air with a low relative humidity. Further discussion of transpiration is presented in Section 7 on soil moisture.

4.2 Factors Affecting Atmospheric Humidity

4.2.1 Macroclimatic factors

The **regional air mass** largely determines the vapour pressure and relative humidity near the seedling. The humidity of the air mass is modified by the land and water surfaces over which it has passed. These surfaces supply moisture to the air by evapotranspiration or remove it by condensation and precipitation.

4.2.2 Site factors

Site factors such as **geographic location** and **elevation** have a relatively small influence on the atmospheric vapour pressure.

4.2.3 Vegetation factors

The vapour pressure, relative humidity, and temperature of the air within a vegetation canopy 1 m or less in height are similar to conditions above the canopy. A small increase in vapour pressure can develop beneath tall, dense canopies. Conditions below these canopies feel cooler and more humid to humans than in the open, largely because of the reduction in the amount of solar radiation heating of our bodies.

4.3 Site Preparation and Atmospheric Humidity

Site preparation will have little effect on the amount of water vapour in the air. However, the relative humidity and vapour pressure deficits can be affected through changes in the temperature of the air near the seedlings. Air temperature close to the ground in a clearcut can be 3 to 6°C warmer than at 2 m (see Section 6 on air temperature).

5 WIND

5.1 Effect on Seedlings

Wind has little direct effect on seedlings, but it can cause blowdown, break branches, or bend the stems of larger trees. The edge of cutblocks and leave strips are particularly susceptible. Wind scour may remove the insulating snow, exposing seedlings to adverse conditions.

An increase in wind speed has a negligible effect on water loss from conifers. The still layer of air - the boundary layer - surrounding a conifer needle is extremely thin. Increasing the wind speed has little influence on the thickness of this layer. Larger evaporating surfaces such as broad-leaved plants, and the surface of puddles, ponds, and the soil have a thicker boundary layer which is more sensitive to changes in wind speed. Consequently, greater wind speeds increase the evaporation rate from a wet soil surface and to some extent the transpiration rate of broad-leaved competing vegetation, but have little effect on seedling transpiration.

The concept of wind chill applies only to objects that generate heat such as animals or houses. Leaves and stems of plants can not be wind chilled. Wind increases mixing of the air so that the temperature of the plant more closely approaches that of the surrounding air.

5.2 Factors Affecting Wind

5.2.1 Macroclimatic factors

The wind speed at a site is mainly determined by large-scale meteorological processes. Differences in solar heating of the ground surface create large scale temperature variations which result in variations in air pressure. The air moves, i.e., the wind blows, in response to these differences in pressure. A greater temperature difference results in a greater difference in pressure and stronger winds.

5.2.2 Site factors

Local topography can reduce or increase ground level winds. For example, wind speeds can increase as the air flows over a ridge and be much reduced in the lee of the ridge. Daytime heating in valleys can generate up-slope (anabatic) winds as the warmer, less dense valley air rises up through the cooler up-slope air. The winds generated during a forest fire are an example of the extreme effect of the upward movement of warm air. Down-slope and down-valley (katabatic) winds occur at night as the cooler, denser up-slope air flows down the slope. A glacier at the head of a valley can create strong katabatic winds during the daytime.

5.2.3 Vegetation factors

Removing vegetation canopies increases the wind speed near the ground. The size and shape of cutblock openings affect wind flow patterns and wind speed.

5.3 Site Preparation and Wind

Wind is of greatest concern to forestry operations in its ability to cause blowdown. The potential for blowdown is affected by the location of cutblock boundaries and leave strips (Moore 1977) and the depth of rooting of the trees. High wind speed areas such as the top of ridges or below saddles should be avoided, and the long axis of the clearcut should be at right angles to the wind. Sharp indentations and square corners in cutblock boundaries should also be avoided. Partial cutting, leaving clumps of trees, and multiple entries over a number of years, are recommended harvesting methods for high risk windfall areas (Alexander 1986).

Wind speed can influence snow accumulation and melt. Clearcut areas exposed to strong winds could lose snow cover through increased scouring, drifting, and sublimation of the snow.

6 AIR TEMPERATURE

6.1 Effect on seedlings

Air temperature has a considerable influence on seedling growth and survival. Physiological processes such as photosynthesis and respiration involve biochemical reactions that are temperature-dependent, as shown in Figure 1. Physical processes such as transpiration are also temperature dependent. In the interior regions of the province, frost damage is a widespread problem.

For most tree species, growth rates are negligible at temperatures below 2 to 5°C. Serious frost damage or mortality can occur if the temperature drops below -2 to -5°C during the active growing season when the seedling is not in a hardened condition. Growth rates are usually suboptimal when temperatures are below 15°C, optimal in the 15 to 25°C range, and increasingly suboptimal as temperatures rise above 30°C. Physical tissue damage and mortality can occur if temperatures exceed about 50°C. The degree and extent of damage, however, depends on the duration and intensity of high temperatures as well as on the type of tissue that is affected.

6.2 Factors Affecting Air Temperature

Air temperature near the ground has a wide diurnal and annual variation. Figure 5 shows the annual variation in daily maximum and minimum temperature of the air and soil in a clearcut with no surface shading. **Solar radiation** is absorbed at the surface during the day, and is dissipated through the net loss of **longwave (thermal) radiation, heating the air and soil**, and **evaporation**.

The amount of longwave radiation emitted from any surface increases with increasing temperature. Since the sky is colder than the ground surface, more longwave radiation is emitted from the ground toward the sky than is emitted from the sky back toward the ground. This net loss of longwave radiation from the ground surface causes it to cool. Nighttime cooling is mainly through this net loss of longwave radiation. Heat stored in the soil profile and overlying atmosphere are transferred toward the cooling ground surface, resulting in a reduction in soil and air temperatures through the night. The ground surface temperature can continue to drop as long as there is a net radiative loss of heat from the ground toward the sky. Daily minimum temperatures thus usually occur at sunrise.

As a result of these energy exchanges, the largest temperature variation occurs at the ground surface and around the seedling. The air temperatures 2 m above the ground can often be 3 to 6°C cooler during the day and 2 to 5°C warmer at night than close to the surface, particularly under calm, clear conditions (Figure 5).

The **density** of air increases as it cools. On a level site, this creates a stable air layer with a temperature inversion that tends to suppress atmospheric mixing. On sloping sites, the increased density of colder air causes it to flow down the slope.

Frost occurs when the surface temperature of the ground or the seedling drops to 0°C or lower. Two different processes cause frost and affect its occurrence throughout the landscape. **Radiation frosts** occur on calm, clear nights when the ground surface cools to 0°C as it radiates heat toward the atmosphere. **Advection frosts** occur when air that has radiatively cooled to or below the freezing point at another location flows, or is blown (is advected) onto a site. An air mass with a sub-zero temperature moving over an area is a macroclimatic scale advection frost. Radiation and advection frosts often occur at the same time.

Macroclimatic, site, surface and vegetation factors combine to produce radiation frost, and the development of frost prone sites. This is explained in detail in Stathers (1989). The major factors affecting air temperature are summarized in Table 2.

6.2.1 Macroclimatic factors

Weather conditions largely determine the air temperature near the ground. Of major importance is the amount of solar radiation available to heat the surface. **Cloud cover** reduces both daytime solar heating and longwave cooling and, as a result, reduces diurnal temperature variation. The origin and history of the air mass also affects its temperature. Increasing the water vapour in the air increases

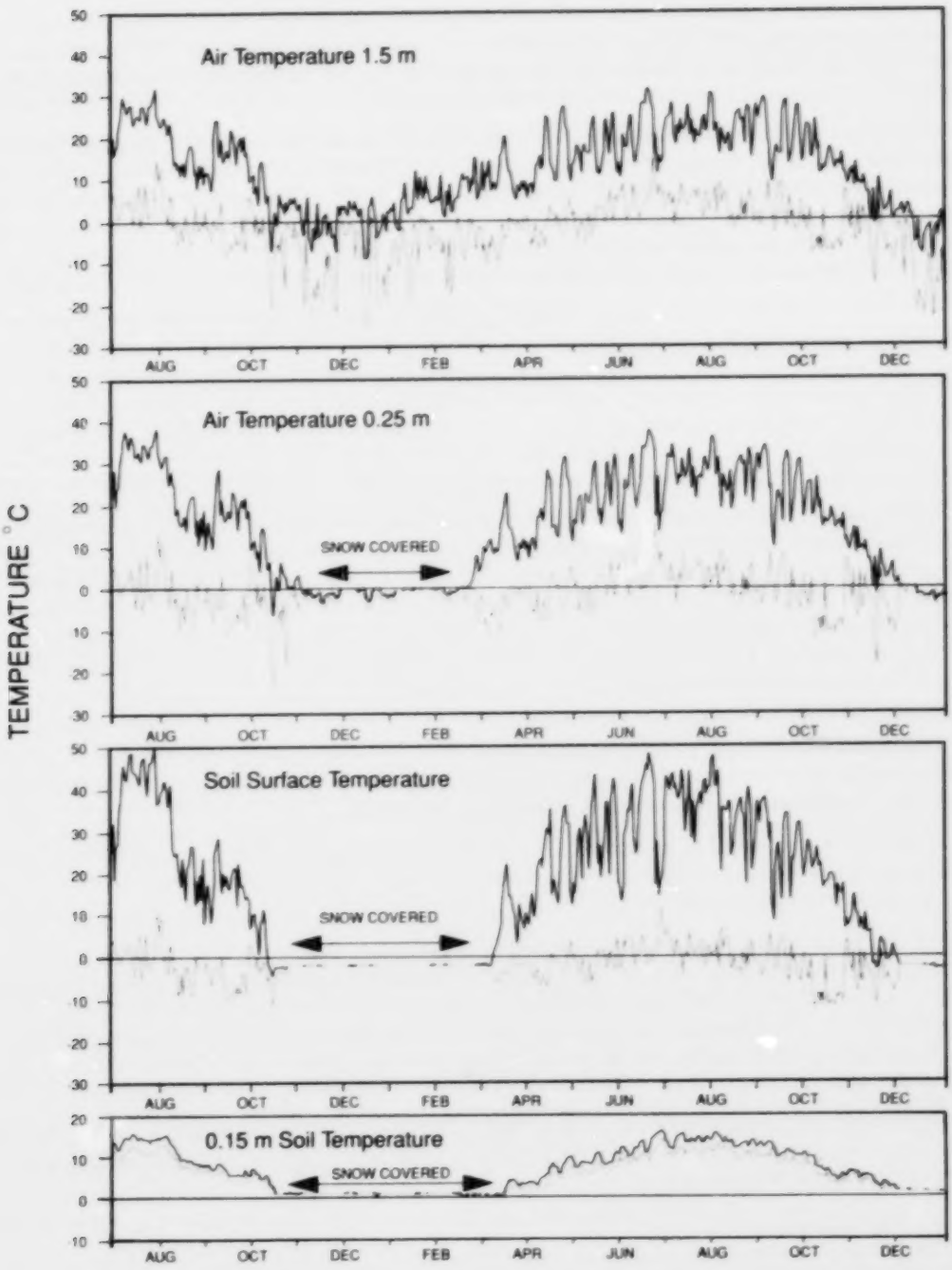

FIGURE 5. Annual variation in the daily maximum and minimum air and soil temperatures in a clearcut in the Montane Spruce zone in the Hurley River valley near Gold Bridge.

TABLE 2. Macroclimatic, site, vegetation, and soil factors that influence air temperature

Category	Factor	Influences
Macroclimate	Cloud cover	solar radiation and downward longwave radiation
	Air temperature	longwave radiation
	Air humidity	longwave radiation and heat release by condensation
	Wind speed	mixing of the air
Site	Elevation	atmospheric conditions
	Slope angle	cold air drainage
	Topography	cold air drainage and wind
	Slope position	size of uphill cold air source
	Slope, and Aspect	solar radiation receipt for air and soil heating
	Latitude	day length, weather conditions
Vegetation	Cover	wind speed, cold air drainage, longwave radiation balance, and soil heating
Soil	Composition	soil heat storage and release
	Water content	evaporative cooling, and heat storage

the longwave radiation emission from the atmosphere to the ground surface. Higher **wind speed** influences air temperatures near the ground by increasing mixing of the air near the surface with the air higher up in the atmosphere.

A combination of clear sky, low wind speed, and dry air can result in the occurrence of frost. The clear night sky produces a large net loss of longwave radiation, and a low wind speed minimizes the mixing of cold surface air with the warmer air well above the surface. The cooling rate of the air is reduced when condensation and dew or hoar frost form. Consequently, the risk of radiation frost is greater in arid and higher elevation areas where the air is initially drier at sunset.

6.2.2 Site factors

Site factors influence air temperature through their effect on the local surface energy balance. **Geographic location** influences the climatic regime of the site. Air temperature generally decreases with increasing **elevation**, partly in response to the changes in weather conditions that occur with increasing elevation. Nighttime longwave radiative cooling is greater at higher elevations in the same climatic regime. **Latitude** influences day length and thus the length of time for daytime surface heating or nighttime cooling.

Slope and **aspect** significantly influence the amount of solar energy received (Figure 2), such that southerly aspects tend to be warmer than other slopes, though the temperature is still dominated by that of the regional air mass. The slope and **topography** of a site influence cold air drainage and accumulation, and frost occurrence. Air that is radiatively cooled at higher elevations flows down slopes and accumulates in low-lying areas, where it ponds to increasing depths while continuing to cool radiatively. Only a slight depression may be sufficient to cause ponding and formation of a frost pocket. The size of the source area for the cold air influences air temperatures where the air pools.

Figure 6 shows how nighttime minimum temperatures at the ground surface can vary along a slope during the summer. Damaging frosts typically occur on flat terraces along the slope where air flow is reduced, and in the lower areas where cold air accumulates.

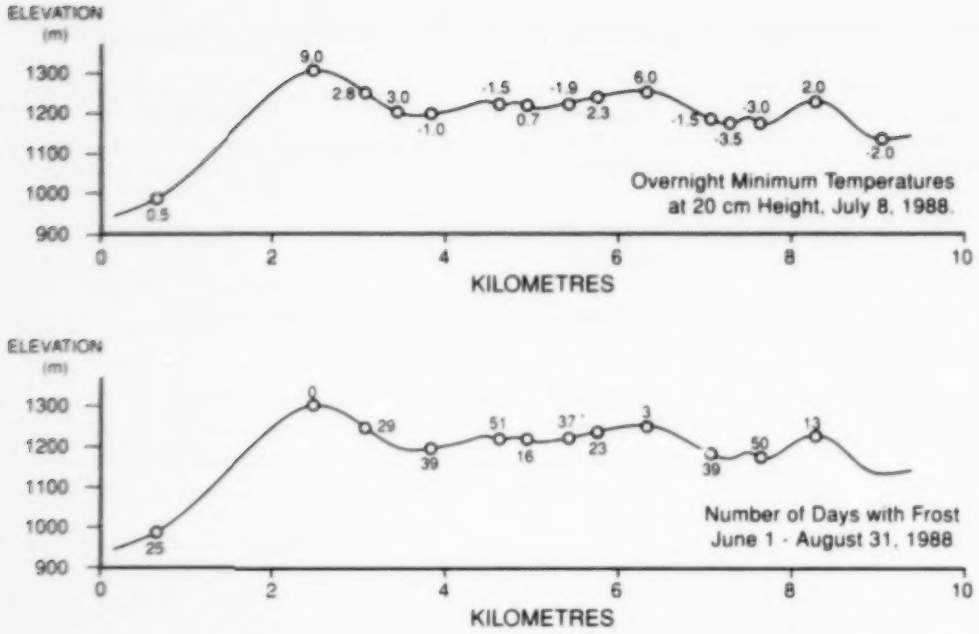

FIGURE 6. Topographic profile showing minimum air temperatures at the 20 cm height on a typical radiation frost night, and the number of days of frost from June 1 to August 31, 1988 in the interior Douglas-fir zone near 100 Mile House. (O. Steen, B.C. Forest Service, unpublished data.)

6.2.3 Surface factors

Vegetation that shades the surface decreases air temperature extremes for seedlings. Shading reduces daytime solar heating and longwave radiative cooling at the soil surface by shifting the majority of the radiative transfer from the surface into the vegetative canopy. Heavy brush cover can result in seedling and soil surface temperatures that are close to that of the surrounding air. The reduction in nighttime longwave radiative cooling can reduce frost occurrence. This effect is greatest in tall canopies (e.g., forests, partial cuts, thinned stands and shelterwoods) where the air surrounding the foliage is usually well mixed and warmer than the air near the ground.

Cutblock boundary location can influence the surface air temperature. A boundary across a slope can act as an air dam, resulting in the ponding of cold air and the development of a frost pocket.

The **albedo** or **solar reflectivity** of the surface affects temperatures around the seedling. Dark-coloured surfaces absorb more radiation and consequently warm more rapidly than lighter surfaces.

Snow acts as an insulator, causing temperatures within the pack to have a much reduced diurnal amplitude (Figure 5). Snow also has a high albedo, and does not absorb as much energy or warm as rapidly as darker surfaces.

6.2.4 Soil factors

The energy balance of the ground surface determines how much of the absorbed solar radiation is transferred into the soil profile and how much is dissipated into the atmosphere as heat or water vapour. Mineral soil surfaces allow more heat conduction into the underlying profile than organic soil surfaces. As a result, air temperatures just above organic surfaces get hotter during the day and colder at night than they do above mineral surfaces.

The moisture content of the soil surface influences air temperature by altering the surface energy balance. When the surface is wet, a larger proportion of the absorbed solar energy is used to evaporate the surface soil moisture rather than to increase soil and air temperatures. Similarly, when the soil is moist, a vegetated surface can be cooler than when the soil is dry, because more of the absorbed energy is lost through transpiration.

6.3 Site Preparation and Air Temperature

Site preparation can influence seedling and soil surface temperatures through changing the absorption and dissipation of energy at the surface. However, this effect is only significant up to about 0.5 m. Shelterwoods and partial cuts can reduce the daily maximum temperature by 1 to 2°C at seedling height compared to a clearcut. They have their greatest effect at night, increasing the daily minimum by 2 to 5°C under certain weather conditions (Odin *et al.* 1984; Hungerford and Babbitt 1987; Stathers 1989).

Exposure of mineral soil by the removal of insulating vegetation and organic layers, e.g., through burning, scalping, trenching, mounding and ripping, has a minor effect on daytime air temperature. However, some studies have found these treatments can decrease the risk of radiation frost damage. The size of the treated spot required to produce the desired protection is not known, though something larger than a small hand-screef is required. Planting in microsites that reduce the amount of cold sky seen by the seedling (its "sky view factor"), e.g., in trenches (Black *et al.* 1988), or that store and radiate energy back toward the seedling at night, e.g., near large stumps and fallen logs, can also reduce the frost hazard. Harvest methods can regulate the flow of cold air over the landscape. Cutblock boundaries should be designed so that they do not obstruct cold air drainage pathways. Site preparation treatments can reduce, but not eliminate, the frequency and severity of summer frost. They are not sufficient to prevent frost on all sites, for example, in low lying spots that have a continuous supply of cold air throughout the night.

7 SOIL MOISTURE

7.1 Effect on seedlings

Newly planted seedlings only exploit a small amount of soil, and are therefore susceptible to water stress. Water stress can be induced through:

- a lack of water, e.g., from low rainfall and removal by competing vegetation;
- a high atmospheric demand for water, e.g., sunny with warm, dry air; or,
- an excess of water, e.g., through the flooding of the root zone by melting snow and restricted drainage.

Also, wet soils are often cold and poorly aerated. Site preparation treatments modify the soil moisture regime either by conserving the available water or removing excess water.

The water potential of the seedling is a measure of its internal water status. It is an integration of the effects of the atmospheric demand for moisture and the ability of the soil to supply water. Plant water potential is the sum of the **turgor potential** (a function of the volume of water in the cell and elasticity of the cell wall), and the **osmotic potential** (a function of the concentration of sugars and starches in the cell).

The turgor potential decreases as the seedling loses water through transpiration during the day. Wilting occurs at zero turgor and further drying can damage the cell. A seedling's osmotic potential decreases slowly over the growing season in response to increasing environmental stresses (Livingston and Black 1987a). This allows it to tolerate greater reductions in water potential, which in turn increases its ability to withstand summer droughts and to harden off in preparation for winter.

The stomata of the leaves are used by the seedling to control the transpiration rate and maintain turgor potential at or above zero. Stomata are affected by a number of environmental variables. Stomatal closure is induced by an increase in air dryness (the vapour pressure deficit), dry soil, light levels below about 10% of full sunlight, frost during the previous night, and low soil temperatures (DeLucia and Smith 1987; Livingston and Black 1987b).

7.2 Factors Affecting Soil Moisture

The seedling's moisture regime can be quantified in terms of a hydrologic balance of water inputs to, and water losses from, the soil profile. This is shown schematically in Figure 7. Changes in soil profile water storage vary with time and depth in the soil depending on the balance between:

- **Input** - precipitation, and down-slope seepage at some sites; and
- **losses** - interception of rainfall, soil evaporation, transpiration, runoff, redistribution in the soil, and drainage from the soil.

The factors that control the soil moisture regime are summarized in Table 3.

TABLE 3. Macroclimate, site, soil and vegetation factors that determine the soil moisture regime. The influence of each factor on the input or output of water in the hydrologic balance is shown

Category	Factor	Influences
Macroclimate	Solar radiation, Air temperature Air humidity, and Wind speed	transpiration and soil evaporation
	Precipitation	input of water
Site	Geographic location, Elevation, Aspect, and Slope angle	solar radiation, air temperature, relative humidity, and precipitation
	Slope position	soil drainage and runoff
Soil	Texture, Coarse fragments, Bulk density, and Organic matter	available water storage capacity, drainage and soil evaporation
	Profile depth	soil water storage
	Profile discontinuities	drainage
Vegetation	Height, Cover (leaf area), and Species	interception of precip., and transpiration
	Rooting depth	transpiration

7.2.1 Macroclimatic factors

Precipitation puts water into the soil. **Solar radiation, temperature, humidity (vapour pressure deficit)** and **wind speed** determine the atmospheric evaporative demand for moisture, and therefore affect the rate of depletion of water through soil surface evaporation and transpiration by plants. Solar radiation is the primary source of energy for evapotranspiration.

Variation in weather conditions within a year strongly influences seedling survival and growth. The **seasonal distribution of rainfall** can sometimes be more important than the total amount. For example, at a site in the Interior Douglas-fir zone near Kamloops, the 1986 growing season had a total of 226 mm rain, and a period of 45 days with no rain. The 1987 growing season had only 155 mm of rain, but the longest dry period was only 25 days. Better seedling survival and growth occurred in 1987 because of the shorter period of drought (Black *et al.* 1987, 1988).

Yearly variations in weather are also important. Figure 8 shows this for a site near Pemberton, B.C. (Spittlehouse and Childs 1990), where there is a large variation in the availability of moisture in the late spring and early summer. The years are classified as adequate, marginal, or too dry for good survival even with control of competing vegetation. These three categories occurred, respectively, 35, 44, and 21% of the time.

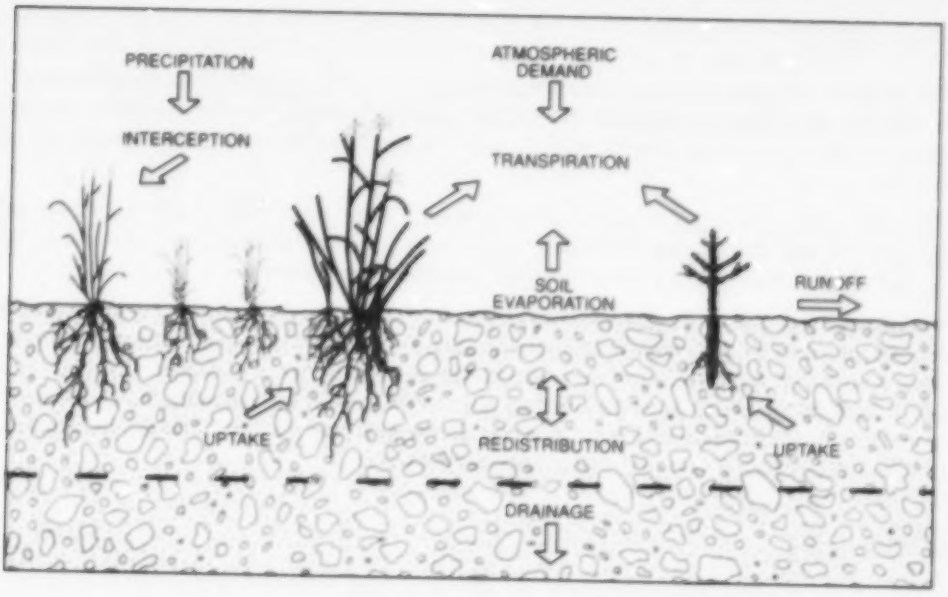

FIGURE 7. Schematic diagram of the hydrologic components of a seedling's environment.

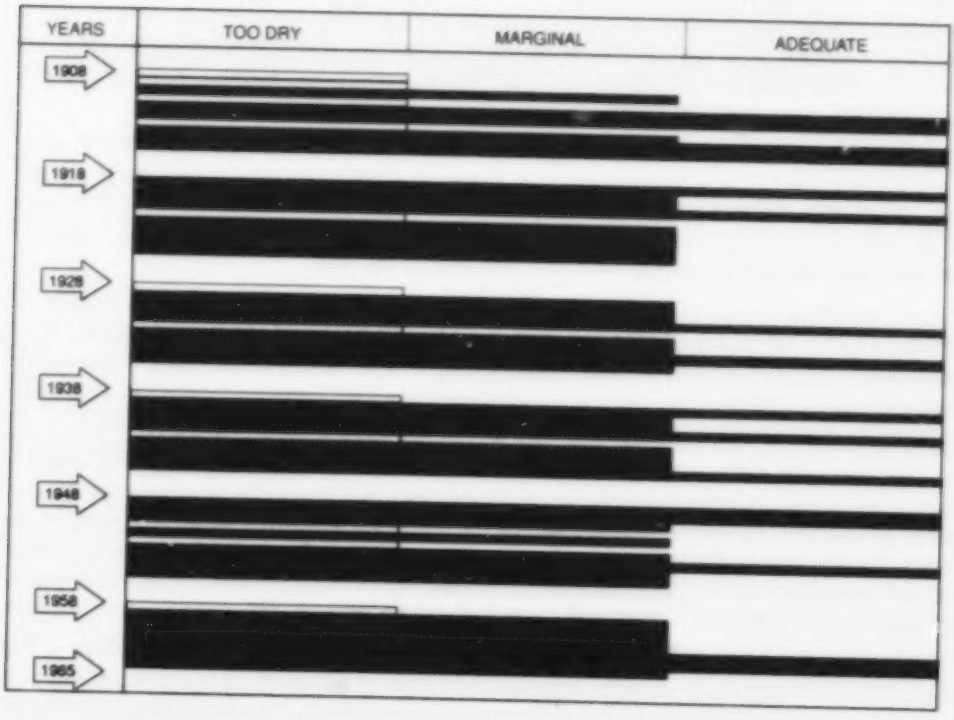

FIGURE 8. Year to year variation in spring planting conditions at a dry site near Pemberton. (Adapted from Spittlehouse and Childs 1990.)

7.2.2 Site factors

The amount and pattern of precipitation is influenced by the **geographic location** (e.g., coastal versus interior), **elevation** and **aspect**. Precipitation generally increases with elevation, particularly on the windward side of mountain ranges. In B.C., the east-facing sides of mountain ranges are often in a rain shadow.

The movement (drainage) of water within and out of the soil profile is influenced by the **slope position** and **micro-topography**. The tops of slopes tend to be well drained, while the low areas tend to receive water from up-slope; and mounds tend to be drier than hollows.

The energy available to evaporate water (solar radiation) is influenced by the **elevation** and **geographic location** (i.e., the regional climate/weather regime of the site), and **slope** and **aspect** which affect the amount of solar radiation received at the ground under a particular climatic regime. For example, a 20% south-facing slope can receive about 15% more solar radiation than a flat surface, and 40% more than a 20% north-facing slope over the course of a year (Figure 2). South-facing slopes have earlier snow melt, and their growing season starts earlier.

7.2.3 Soil factors

Soil is a three phase system composed of solids and voids (pores), the latter containing air or water. The number, size, shape, and continuity of the pores determine the hydrologic characteristics of the soil, i.e., soil water retention, redistribution, and drainage.

Soil water retention and availability

The soil is an important water reservoir for seedlings during rainless periods. The amount of water that can be stored in the soil (the soil water retention capacity) depends on the soil texture and stoniness. The fine fraction (less than 2 mm in diameter, the sand, silt, and clay particles) influences the number and size of pores that hold water. The coarse fragments (particles greater than 2 mm in diameter) occupy space that could otherwise hold water.

Water is held in the soil pores by its attraction to the adjacent soil particles (adhesion) and by the attraction between water molecules (cohesion). Pressure must be exerted to counteract these forces to remove water from the soil pores. The negative value of this pressure, the soil water potential, is expressed in units of megapascals (MPa) or bars (1 MPa = 10 bars). A plot of the soil water potential versus soil water content is the retention characteristic of the soil.

A soil is saturated when all the pores are full of water. The large pores drain easily since most of the water in them is not held tightly. As the soil dries, an increasing amount of pressure is required to remove the water from smaller and smaller pores. This is one reason why the likelihood of plant water stress increases as the soil dries.

Between 20 and 50% of the water that can be contained in a volume of soil is considered available to plants. This **available water storage capacity** of a soil is defined by upper and lower limits of soil water potential. **Field capacity** is the maximum amount of water that the soil can store within a few days after a large rainfall when the drainage becomes negligible. The water held in the larger soil pores usually drains out of a saturated soil profile with a few days, and is not generally available to plants. Field capacity occurs at water potentials of -0.01 to -0.03 MPa. **Permanent wilting point** is the water potential at which the soil is too dry for plants to extract water (-1.5 to -2.5 MPa).

Pore size distribution (soil texture) determine the relative volume of water in the soil available to the plant. The available water storage capacity of a range of soil textures is shown in Figure 9. Sands have a smaller capacity than clays, which have a smaller capacity than loams (ratio 1:1.3:1.6). Clays have the largest volume of pores, but much of the water is at a potential lower (drier) than the permanent

wilting point. In contrast, much of the water-holding capacity of sands is above field capacity. **Bulk density** affects the pore space available to hold water. Increasing the bulk density by compacting a soil decreases the number of large pores and reduces the water storage capacity.

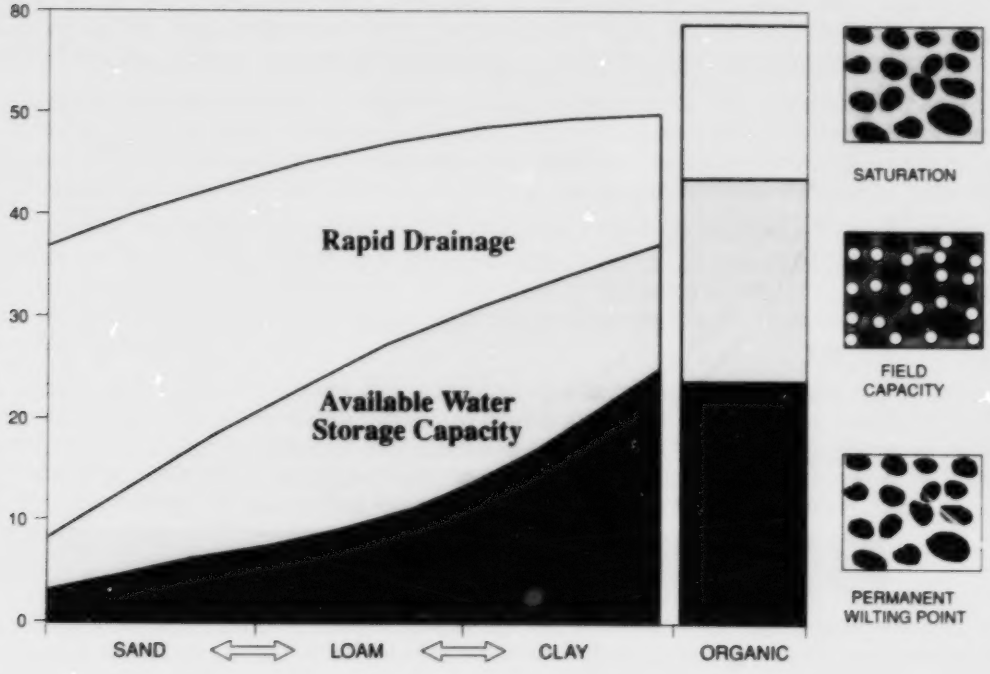

FIGURE 9. Available water storage capacity and soil texture.

Coarse fragments reduce the available water storage capacity of a soil in proportion to the coarse fragment content. For example, a 20 cm thick layer of loam soil has a water storage capacity of 320 mm. A 30% coarse fragment content on a volume basis (70% fine fraction) would reduce the capacity to 320 x 0.7 = 224 mm. **Depth of the soil** determines the total amount of water storage. A deeper soil can store more water than a shallow soil.

Organic matter improves the water retention properties of soils when present in small amounts. It has its greatest effect in coarse-textured soils. The degree of decomposition of the organic material affects the water retention properties. Undecomposed organic material, e.g., a surface litter layer, is loose, with large pores. It has a low available water storage capacity, since most of the water can easily drain out of the layer. The available water storage capacity of a partially decomposed surface organic layer (Figure 9) is high due to its larger proportion of small pores.

Figure 10 shows how soil texture and coarse fragment content affect the water available to maintain seedlings during periods without rain. The figure shows the decrease in available water over time, starting at field capacity, for a block of bare soil containing a seedling. Water is removed through

transpiration and evaporation from the bare soil surface. The difference in available water storage capacity between the sand and loam (Figure 10) is reflected in the longer drying time for the loam. Water stress can develop rapidly in sandy soils with infrequent growing season rainfall. The influence of coarse fragment content on the rate of soil drying is shown by the middle line in Figure 10, where a coarse fragment content of 25% has been added to the loam. The percent coarse fragment content reduces the number of days to reach any soil water content by about 25%.

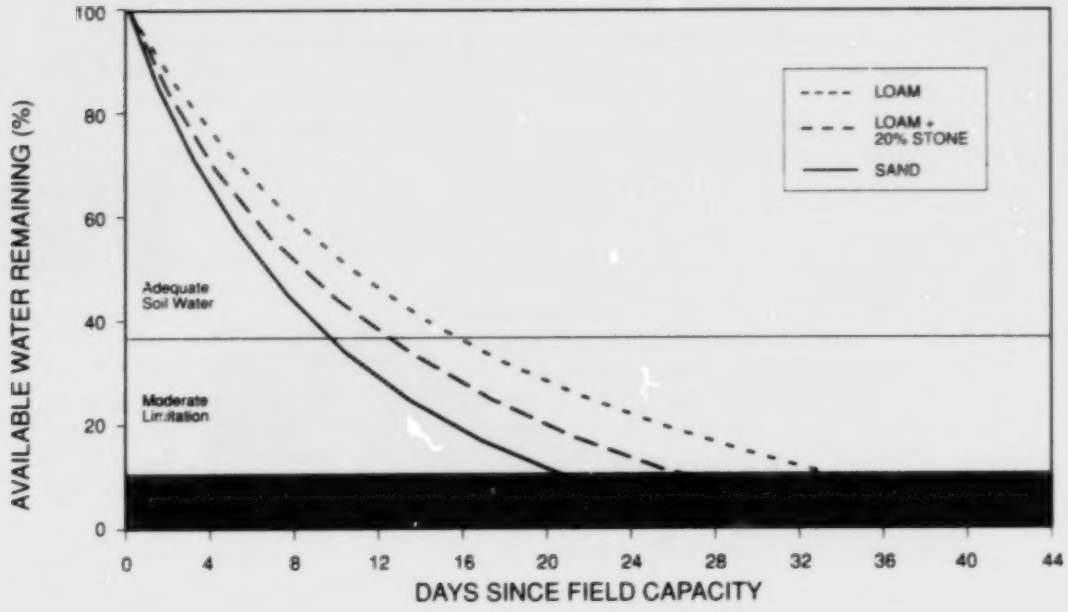

FIGURE 10. The effect of soil texture and stone content on soil water depletion after planting.

Soil water supply can usually meet atmospheric evaporative demand when most of the root zone is wetter than about -0.2 MPa. This is equivalent to having greater than 35% of the available water storage capacity filled. As the root zone continues to dry, the transpiration rate becomes limited by the rate at which the soil can supply water to roots. Consequently, processes such as transpiration, photosynthesis, and growth are slowed because of the development of internal water stress. Most plants usually stop growing when the soil water potential declines to about -1 MPa (available water storage of about 15%). At the permanent wilting point most plant species are often desiccated and under severe internal water stress. Transpiration stops when all the available water has been depleted. The difference between the atmospheric evaporative demand for water and the actual transpiration from plants is termed the **water deficit**.

Soil water flow

Movement of water into and through the root zone is important for maintaining soil water availability and aeration. Water flows from high to lower soil water potentials, that is, from wetter to drier regions within the soil profile. The ability of the soil to conduct water - the **hydraulic conductivity** - depends on a number of factors.

Soil texture and **structure** influence the size, shape and continuity of pores. Cracks, wormholes, and root channels have a high hydraulic conductivity and allow rapid water flow. The smaller pore sizes have a lower hydraulic conductivity. **Bulk density** affects the sizes of pores. Within any one soil textural class, an increase in bulk density decreases the hydraulic conductivity of the soil. Compaction and puddling of soils increase the bulk density and may even seal off pores, greatly reducing water flow through the profile. **Coarse fragment content** has only a minor effect on hydraulic conductivity.

Water content determines which pores are filled with water. As the water content decreases, only smaller pores remain filled with water, the path for movement becomes less direct, and the hydraulic conductivity and rate of flow decrease. **Temperature** affects the viscosity of water. The hydraulic conductivity decreases as temperature decreases because the viscosity of water increases.

Coarse-textured soils have a greater percentage of large pores than fine-textured soils. This gives them a high hydraulic conductivity when saturated, but a rapidly decreasing conductivity as these large pores dry out. As fine-textured soils dry below field capacity, the larger number of undrained, smaller pores results in a higher hydraulic conductivity than in coarse-textured soils at the same water potential.

The flow of water through the soil profile is also affected by large changes with depth in the hydraulic conductivity. These changes, termed **profile discontinuities**, can be caused by changes in soil texture, e.g., from coarse to fine and vice versa, or compacted or cemented layers. They reduce or stop water flow, often resulting in saturation and the formation of a perched water table well above the general groundwater level.

The relationship between pore size, water content, and hydraulic conductivity is important for such phenomena as the formation of **ice lenses** and **needle ice**. Water tends to move from warmer to cooler layers. The hydraulic conductivity of medium- to fine-textured soils near field capacity allows a significant amount of water movement toward a frozen zone, resulting in the formation and growth of ice lenses. The accumulation of ice can force poorly rooted seedling plugs out of the ground (**frost heaving**).

Surface runoff

Runoff occurs when the rainfall rate is greater than the rate that water can infiltrate into the soil. This usually only occurs with fine-textured or compacted soils. If the site is flat, then ponding rather than runoff may occur. Runoff also occurs when the water table rises to the surface so that the soil is saturated. This situation usually occurs in hollows or at the bottom of slopes.

A dry organic layer, particularly one that has been burned, may cause runoff during the first part of a rainstorm. This occurs because the organic material is hydrophobic (i.e., it repels water) and it requires time to reduce the hydrophobicity.

Soil surface evaporation

Soil surface evaporation removes water from the seedling root zone. **Weather conditions** and the amount of **shading by vegetation** determine the atmospheric demand for moisture by regulating both the amount of solar radiation reaching the soil surface and the wind speed. **Soil texture** and **soil water content** determine the rate at which the soil can supply water (hydraulic conductivity of the soil) to the surface for evaporation, and the amount of water available for evaporation.

The soil dries first in the top 1 to 2 cm of the profile. This dried (mulched) layer has a low hydraulic conductivity, resulting in a much-reduced soil evaporation rate. Organic surface layers and sands mulch more readily than fine-textured soils. The higher unsaturated hydraulic conductivity of fine-textured soils allows greater water movement toward the surface from deeper layers. It takes about 15 days with little rain to dry the top 5 to 10 cm of an exposed mineral surface to the permanent wilting point. If there is no vegetation, the soil at the 15 to 20 cm depth will still be moist.

7.2.4 Vegetation factors

Vegetation affects both the input and output components of the hydrologic balance.

Interception of Precipitation

Precipitation intercepted by the vegetation evaporates rather than infiltrates into the soil. In the case of short vegetation, interception is only significant for rainfalls of less than 3 mm. In forests and shelterwoods, rainfall of less than 5 mm is almost totally intercepted by the canopy foliage. Between 10 and 30% of the rainfall from larger storms is intercepted, depending on the canopy density.

Transpiration

Soil water uptake by competing vegetation can rapidly deplete water stored in the root zone. The transpiration rate depends on the atmospheric demand for water, the ability of the soil to supply this water and the amount of competing vegetation. Increasing the amount of vegetation cover increases the rate of water loss. However, this peaks at a leaf area index (area of leaf per unit area of land) of about 4. Soil surface evaporation decreases with an increase in shading. Vegetation tends to deplete water from the surface layers of the soil at a greater rate than in the lower layers because of the generally greater root density near the surface.

Figure 11 shows the effect of a partial vegetation cover on the rate of water loss from a 20 cm deep block of soil (loamy clay) containing a seedling. The water loss rate from a similar bare soil surface is also shown. As might be expected, the vegetation cover significantly increases the rate of soil drying. Figure 11 shows that frequent growing season precipitation is required to maintain favourable conditions for seedling growth on sites where the vegetation is not well controlled.

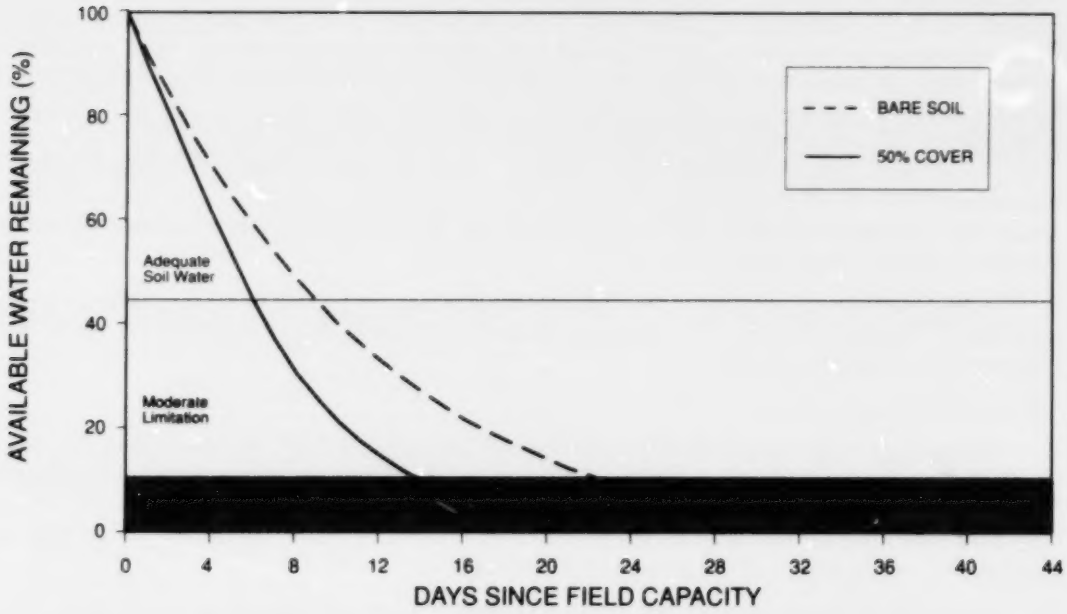

FIGURE 11. The effect of vegetation cover on soil water depletion after planting, for a loamy clay.

7.3 Site Preparation and Soil Moisture

Site preparation and vegetation management treatments can be used to increase root zone soil water storage and conserve soil water for seedling use, or to remove excess water from the root zone (Spittlehouse

and Childs 1990). The effects of various site preparation treatments on the soil moisture regime are summarized in Table 1.

Water conservation treatments involve reducing transpiration by killing or removing the competing vegetation through the use of herbicides, prescribed burning, or mechanical devices. Herbicides can create a surface organic mulch which further increases water conservation by reducing soil evaporation (Flint and Childs 1987; Black *et al.* 1987, 1988). The degree of water conservation and the duration of its effect vary with the treatment intensity and the type of vegetation under control. In more specialized applications, such as greenhouse or nursery production, organic or plastic mulches can also be used to conserve water by reducing soil evaporation.

Mechanical treatments such as ripping or rotovating increase the soil water storage capacity by changing the soil pore size distribution. Organic matter also is incorporated into the mineral soil (Black *et al.* 1987, 1988). Removal of excess water is used to improve soil warming and aeration of the seedling root zone. Mounding (Draper *et al.* 1985,1988; Örlander *et al.* 1990) and ditching are commonly used to create drier planting spots for seedlings.

8 SOIL TEMPERATURE

8.1 Effect on Seedlings

Soil temperature influences seedling growth and survival through its effect on physical and physiological processes such as respiration or water uptake by roots (Heninger and White 1974; Örlander *et al.* 1990). Low root zone soil temperatures present a widespread microclimatic limitation to the initial establishment of seedlings throughout the province. This is caused either by climatic factors such as deep winter snow packs that melt late in the spring or by site specific conditions that reduce soil profile heating during the growing season.

8.2 Factors Affecting Soil Temperature

Soil profile temperatures are determined by **site location, atmospheric (weather) conditions, ground cover**, and **the physical properties of the soil profile** (Table 4). Soil temperature varies continuously in response to changes in energy receipt and partitioning at the soil surface. The distinct diurnal and annual soil temperature cycles (Figures 5 and 12) are driven by the cycles of solar radiation.

TABLE 4. Macroclimatic, site, surface, and soil factors that determine the soil temperature regime

Category	Factor	Influences
Macroclimate	Solar radiation, Air temperature, Precipitation, and Wind speed	heat transfer into the soil and soil water content
Site	Latitude, Elevation, Slope and Aspect	solar radiation, air temperature, soil water content, and day length
Surface	Vegetation cover, Snow cover, Albedo, and Surface roughness	solar radiation absorbed
Soil	Soil composition, Bulk density, and Soil water content	thermal conductivity, volumetric heat capacity, and heat transfer into the soil

During the day, heat flows into the soil profile as the ground surface absorbs solar radiation. However, most of this solar radiation is transferred into the atmosphere as heat and water vapour. Usually, less than 15% of the energy absorbed at the surface is conducted into the profile. At night, the soil profile cools as heat is conducted upward and emitted from the surface toward the atmosphere as longwave radiation. Thus, during the spring and summer when days are long and warm, the soil profile accumulates heat. During the longer, colder days of fall and winter, the profile cools as it slowly loses this heat to the atmosphere.

On a clear summer day, bare ground surface temperatures sometimes exceed 50°C in clearcuts throughout the province. On the same night, surface temperatures can then drop to near freezing, particularly if the sky is clear. The temperature variation in the seedling root zone is rapidly damped from the extremes that occur at the surface, as shown in Figure 12. At the 0.5 m depth, the temperature normally varies by less than 0.2°C per day. Heat is conducted relatively slowly through the soil profile and, as a result, temperatures at depth increasingly lag behind changes in surface temperature. For example, at 10 cm the lag is about 4 hours (Figure 12).

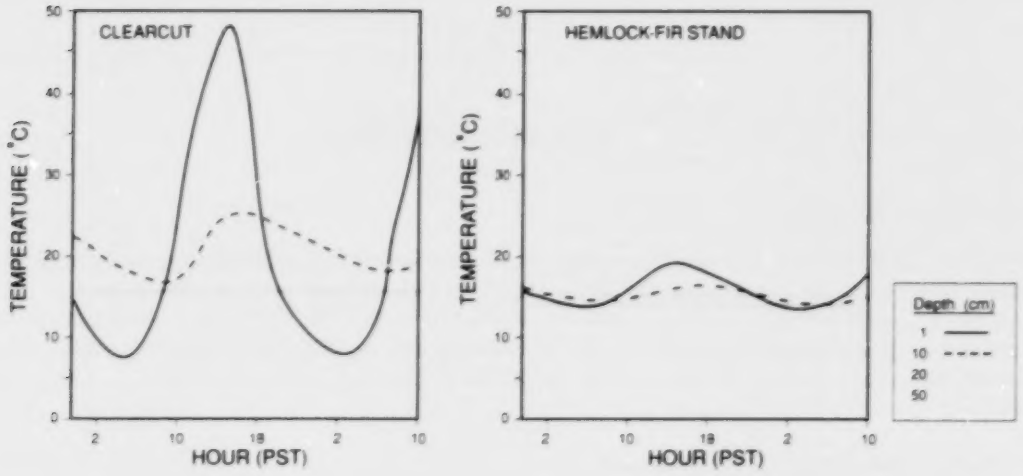

FIGURE 12. Diurnal course of summertime soil profile temperatures in a forest clearcut and adjacent Western Hemlock forest in the Coastal Western Hemlock zone near Port Alberni.

8.2.1 Macroclimatic factors

Solar radiation has the greatest influence of all factors on soil temperature. A large proportion of the variation in soil temperature over the landscape can be attributed to the effects of latitude, elevation, slope, aspect, and surface cover (vegetation cover and snow) on the daily and seasonal duration and intensity of solar radiation. The ground surface temperature warms during the day as it absorbs solar radiation and cools at night as it emits longwave radiation toward the sky.

Cloud cover reduces both the solar radiation during the day and the net loss of longwave radiation from the ground at night. As a result, there is much less soil temperature variation on cloudy days than on clear days.

Precipitation can change the soil temperature as it percolates through the profile. Changes in soil water content also affect the soil thermal properties.

Wind reduces the surface temperature during the day by increasing the rate of heat loss to the atmosphere. Under windy conditions, more of the heat absorbed by the ground surface is dissipated into the overlying air and less is conducted into the soil profile.

8.2.2 Site factors

Latitude influences the soil temperature through its effect on day length. As the number of daylight hours increases during the summer, soil profile heat storage increases because more heat is transferred into the profile during the day and less heat is radiated back to the atmosphere at night.

Elevation influences soil temperature through its effect on the associated weather regime (precipitation, air temperature, and duration of snow cover).

Slope and aspect have a significant effect on the diurnal and annual receipt of solar energy (Figure 2). During the course of a year, steep, south-facing slopes can receive up to twice as much clear sky solar radiation as north-facing slopes. The effect of slope and aspect on solar radiation is greatest in the early spring, late fall, and winter when the solar elevation is lowest. Southerly aspects, which receive more radiation than northerly ones, warm up more rapidly in the early spring. Sloping surfaces often have a drier moisture regime and higher soil temperatures than wetter, level terrain.

8.2.3 Surface factors

Vegetation cover reduces root zone temperatures during the day by absorbing the solar radiation and shading the ground surface. A comparison of soil temperatures in a clearcut and adjacent mature western hemlock forest during a clear, hot, summer day is shown in Figure 12. Although soil temperatures below the 0.5-m depth were quite similar, the diurnal soil temperature variation in the seedling root zone was much greater in the clearcut. The daily maximum surface soil temperature was higher than 50°C in the clearcut, but only 16°C beneath the forest canopy. Surface soil temperatures beneath the forest canopy were similar to the air temperatures during the day.

Vegetation cover increases soil surface temperatures at night by reducing convective and radiative heat loss from the ground surface. At night, temperatures beneath a tall dense forest canopy can be 2 to 5°C warmer than in similar adjacent clearcut areas.

Snow cover acts as an insulating layer that reduces the rate of heat loss from the soil profile during the winter. Snow, a poor heat conductor, keeps the ground surface temperature near 0°C (Figure 5), reducing the depth of frost penetration and, therefore, the amount of heat required to warm the soil profile in the spring. The depth to which soil freezing occurs in winter depends on the duration and severity of cold atmospheric conditions and the depth and duration of snow cover. Cold weather in the late fall before the development of a snow pack, or intermittent snowfall and melting during the winter, can lower soil profile temperatures considerably.

The **albedo** affects the amount of solar radiation that is absorbed at the ground surface. A dark or burned surface absorbs about 95% of the incident solar radiation; a dry sandy soil surface, a brush-covered site, and a mature forest absorb about 70, 80, and 88%, respectively.

8.2.4 Soil factors

The rates of heat storage and transfer within the soil profile are affected by the **volumetric heat capacity** and **thermal conductivity** of the soil. The volumetric heat capacity is defined as the amount of heat required to change the temperature of a given volume of soil by 1°C. The thermal conductivity determines the rate of heat flow through the soil at a given temperature gradient.

Both of these thermal properties can vary considerably within the soil profile. This variation depends on the composition (texture, organic matter content, stone fragment content), bulk density, and water content of the soil. The thermal properties of various soil constituents compared to those of dry sand are shown in Table 5. The air and water fractions in soil displace each other as the soil water content changes.

Since the thermal conductivity and volumetric heat capacity of air are so much less than that of water, the **soil moisture regime** has a large influence on heat storage and transfer within the profile.

Table 5. Thermal properties of soil, peat, air, and water relative to those of dry sand

Material	Volumetric heat capacity	Thermal conductivity	Diffusivity
Dry soil	1.0	1.0	1.0
Wet soil	2.3	7.0	3.0
Dry peat	0.4	0.3	0.7
Wet peat	3.0	1.8	0.6
Air (calm)	0.001	0.1	~100
Water (calm)	3.1	2.0	0.6

The **soil thermal diffusivity**, the ratio of the thermal conductivity to the volumetric heat capacity, provides an index of how readily changes in temperature at the ground surface are transmitted through the profile. The thermal diffusivity of a dry mineral soil is relatively low; however, it increases rapidly as the soil becomes moist, and then declines as the soil water content approaches saturation. As a result, temperature changes are transmitted slowly through very dry or very wet mineral soils. The lower diffusivity and the effect of evaporative cooling explain why wet soils are often much colder than drier soils.

Fine-textured soils often remain cooler than coarser-textured soils during the summer because of their higher water-holding capacity and volumetric heat capacity. Coarse-textured soils tend to develop a dry surface layer (a mulch) more readily than fine-textured soils. A surface mulch decreases both evaporative cooling of the surface and heat flow into the soil profile.

Surface organic layers have a high water-holding capacity. They also have a very low thermal diffusivity at all water contents and, therefore, act as very effective insulating layers. Under clear-sky conditions, soils with dry organic surfaces usually get much warmer during the day and colder at night than mineral soils. This occurs because the low thermal conductivity of organic matter reduces heat transfer into the profile and the low volumetric heat capacity causes a relatively large change in temperature for a small change in heat storage. Figure 13 shows the diurnal variation in soil temperature with depth, in a bare mineral soil profile and a mineral soil covered with a 10 cm surface organic horizon under the same weather conditions. A greater total amount of heat is conducted into the mineral profile during the day and this heat is transferred deeper into the profile. As a result, the mineral soil shows less extreme surface temperature variation and more variation in the seedling root zone. In addition, the daily average temperature at all depths in the mineral soil is higher because more heat accumulates in the profile over the course of the summer.

8.3 Site Preparation and Soil Temperature

Site preparation or vegetation management treatments are often used to improve the thermal regime for seedlings (Table 1). These treatments modify the thermal regime by altering energy exchange at the soil surface and changing the thermal properties of the soil profile. Removing the vegetation that shades the soil surface, by the use of herbicides, prescribed burning, or mechanical site preparation treatments will warm the soil. Mechanical site preparation and burning can cause a greater amount of soil warming by reducing the depth of the surface organic horizon. Exposing mineral soil increases the thermal diffusivity of the surface soil and, therefore, increases heat conduction into the profile. In addition, these treatments reduce surface temperature extremes which can cause seedling heat stress or cold stress (Childs and Flint 1987; Black *et al.* 1988; Örlander *et al.* 1990).

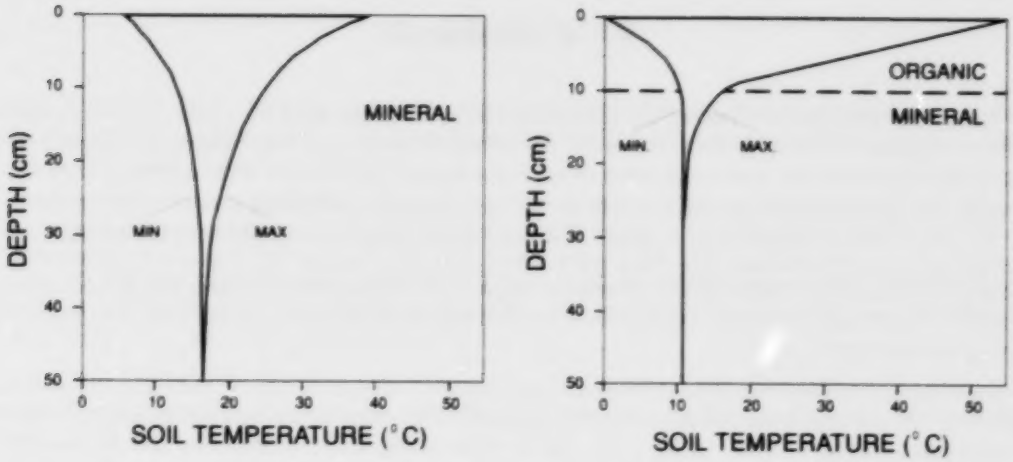

FIGURE 13. Range of diurnal soil temperature variation in a bare mineral soil and a mineral soil covered with a 10 cm deep organic horizon. (Adapted from Cochran 1969.)

Site treatments that mound or ridge the soil improve soil water drainage and drying, resulting in a decrease in the volumetric soil heat capacity and greater warming per unit of stored heat. Mineral soil exposure is particularly beneficial in cold and wet environments. The effect of removing vegetation cover, exposing mineral soil, and creating mounds, on the accumulated growing degree days of the seedling root zone in the Sub-Boreal Spruce zone near Prince George is shown in Figure 14.

In hot, dry environments it is often desirable to expose mineral soil to reduce surface temperature extremes. On a clear summer day, a dry, black, burned organic surface layer can become extremely hot and potentially lethal to seedlings. A small scalped patch can help reduce this high surface temperature around the seedling root collar. Shade cards, shelterwoods, or partial cuts can also be used to prevent the occurrence of high soil surface temperatures (Childs and Flint 1987; Hungerford and Babbitt 1987).

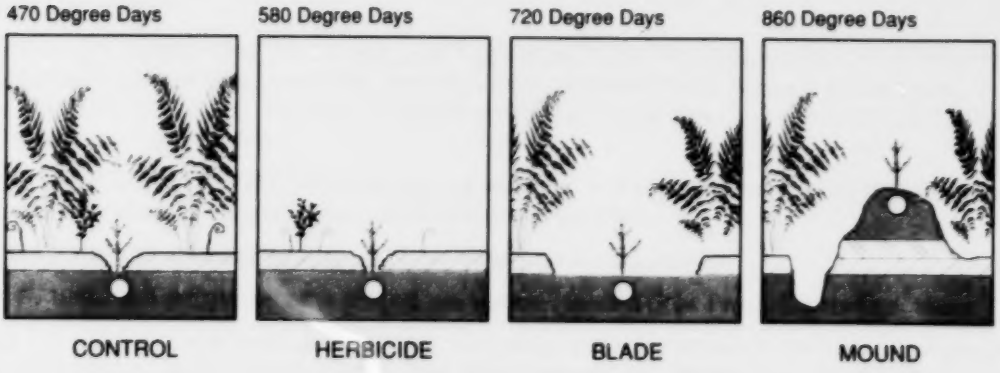

FIGURE 14. The effect of site preparation treatments on accumulated growing degree days at the 10 cm depth (indicated by the open circle) in the Sub-Boreal Spruce zone in the Bowron River valley near Prince George.

9 SUMMARY

Table 1 summarizes how various site preparation treatments can modify the light, air temperature, and soil moisture regimes of planting sites. However, not all modifications are necessarily beneficial and negative effects must be balanced against positive ones. For example, removal of organic matter may improve soil warming, but the increased drying and loss of nutrients may be detrimental in some environments. Consequently, a site treatment such as mounding that improves soil warming but maintains soil nutrients, will be more suitable than scalping at some sites. Also, some treatments may only partially improve the environment for the seedling. For example, herbicides may reduce vegetation competition for light, but in cold environments removal of the insulating surface organic layer is also required to improve soil warming and produce the best growing environment.

It is important to determine which resources are likely to limit growth prior to choosing the site preparation treatment. The limiting resources are ecosystem specific. The effect of different treatments can also vary with the ecosystem being treated. Table 1 can aid in determining which treatments can provide the desired changes. This information can then be balanced against site factors, equipment availability, and cost.

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